Jet Propulsion Laboratory
California Institute of Technology

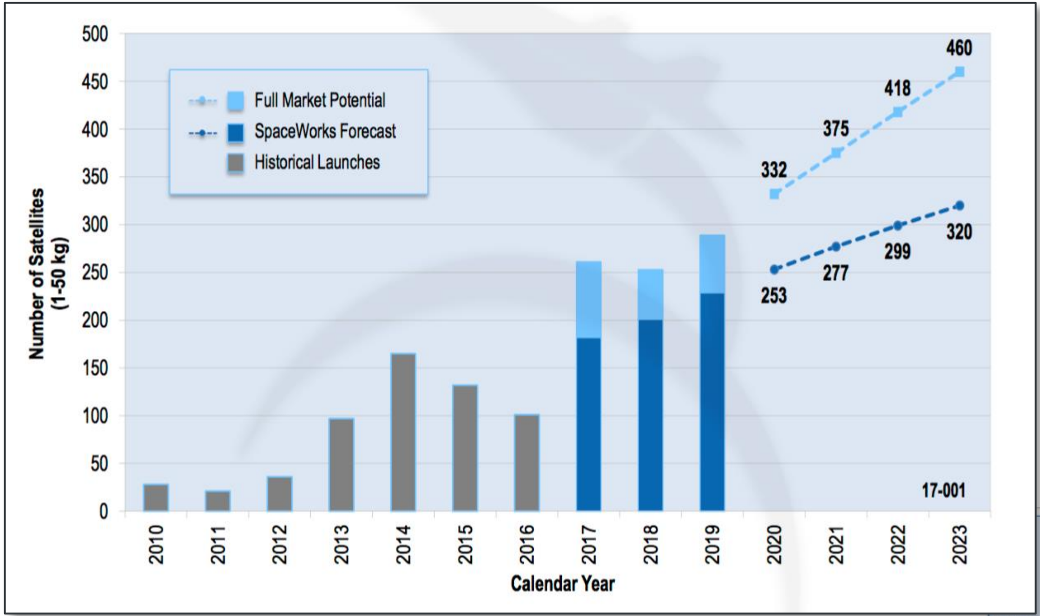
SmallSat Reliability

D.J. Sheldon, Assurance Technology Program Office (ATPO)
Office of Safety and Mission Success
Jet Propulsion Laboratory, California Institute of Technology

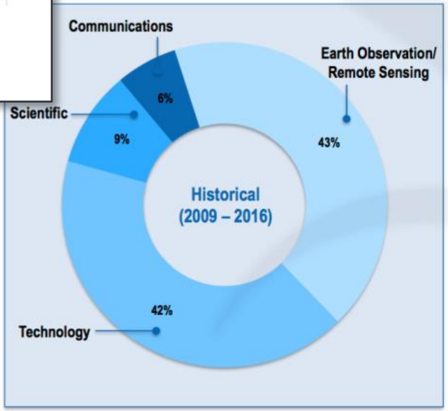
Overview

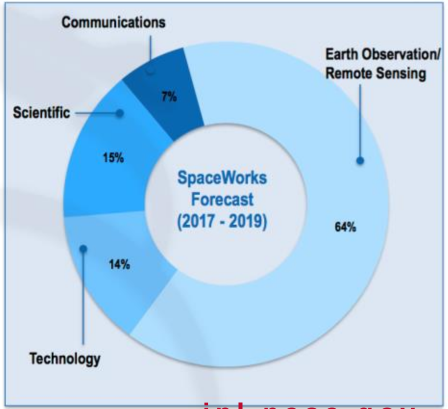
- SmallSat Overview
- Quality and Reliability for Spacecraft Classes
- JPL Assurance Tailoring Process
- Highlights of Recent Mission Activities at JPL
  - EEE parts comparison
  - Inspection analysis
- Deep Space Cube/SmallSats
- Conclusions

SmallSat History and Projections



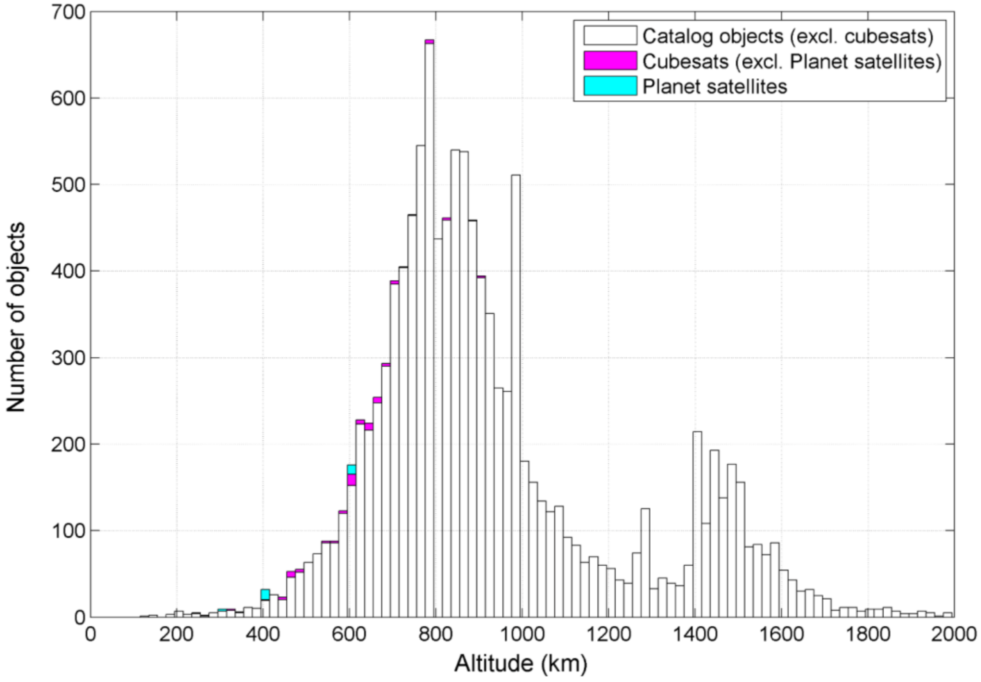
- Between 250 to 400 SmallSat launches ***each*** year for the next 4 to 5 years are planned
- Almost 2,400 SmallSats are planned or announced from 2017 to 2023
- 70% of future SmallSat launches are expected to be by commercial companies, not universities or governments.
- Earth observation and remote sensing are becoming the dominate use for SmallSats





http://spaceworksforecast.com/docs/SpaceWorks_Nano_Microsatellite_Market_Forecast_2017.pdf

SmallSats – Where are they going?

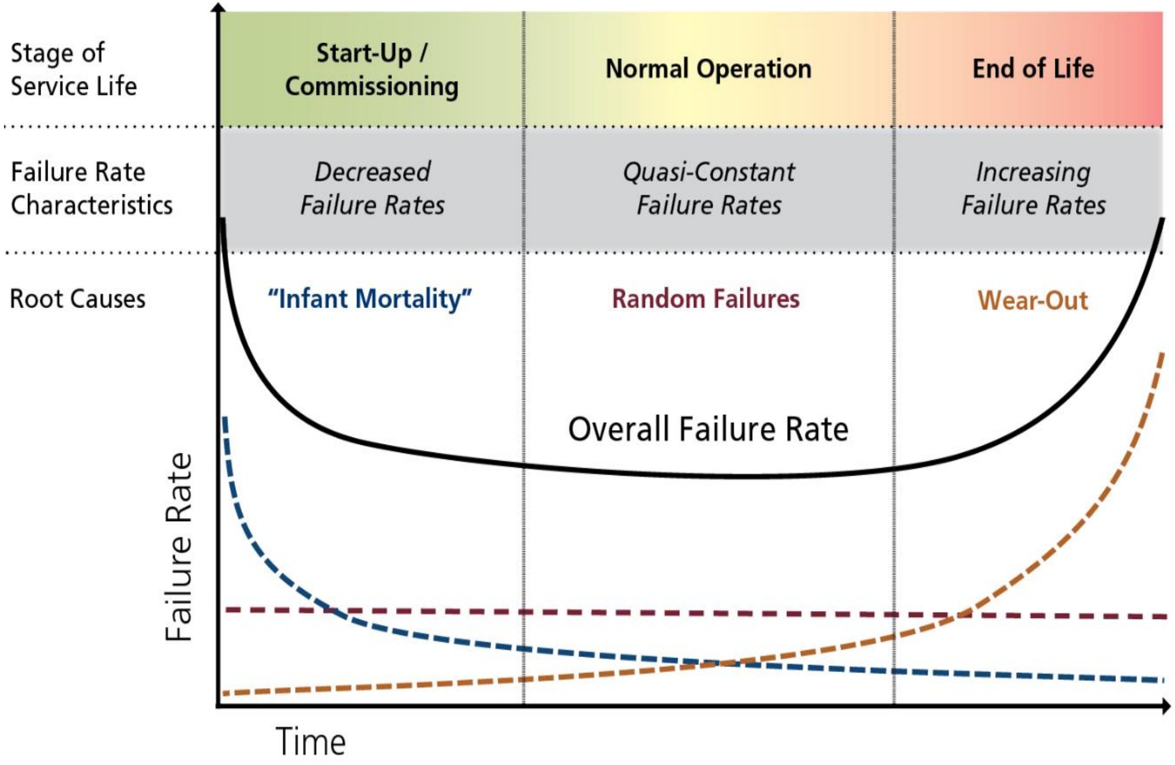


https://www.planet.com/pulse/keeping-space-clean-responsible-satellite-fleet-operations/

- For altitudes > 550km, orbital lifetime > 10 years
- Over 80% of microsatellites launched in the next 3 years are expected to launch to synchronous or polar orbit, as compared to only 39% in the previous 3 year period[1].

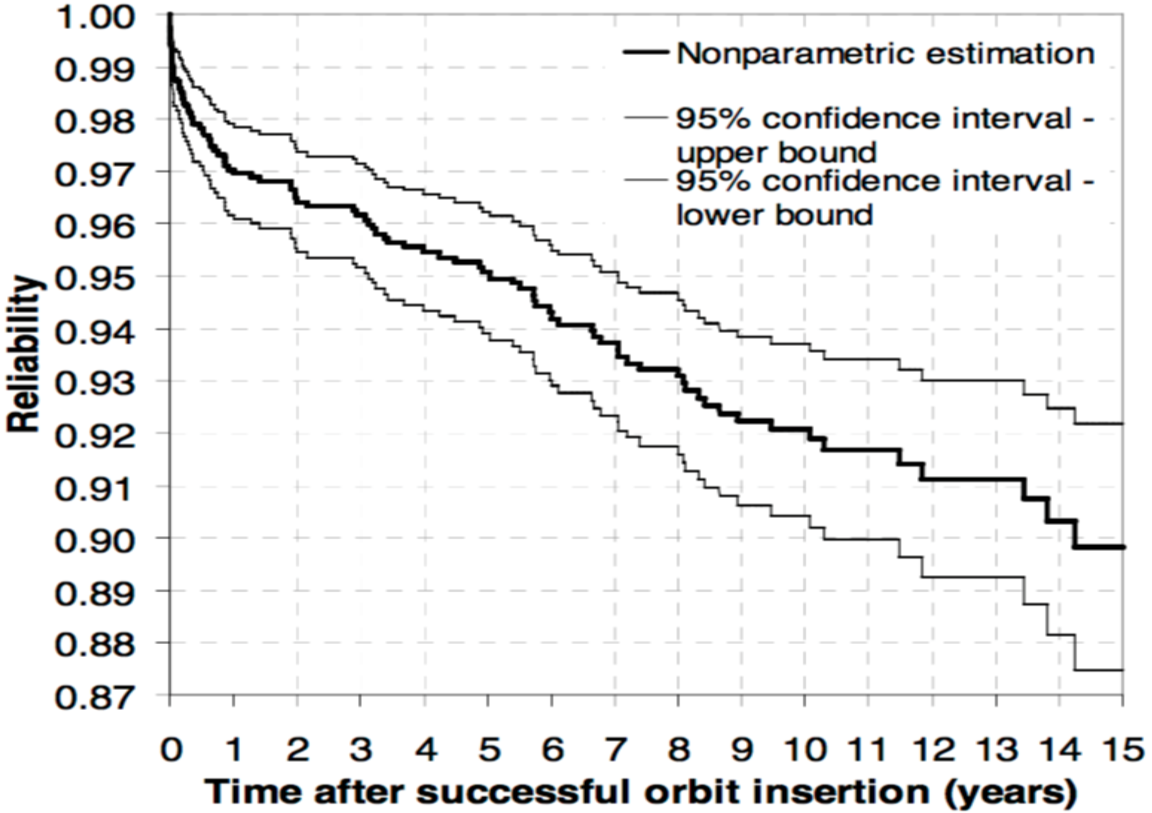
CubeSats STMSat-1, CADRE and MinXSS are deployed from the International Space Station during Expedition 47.***Credits: NASA***

Quality vs. Reliability



- Quality issues (defects) are the root cause for infant mortality region
  - Manufacturing variation
  - Incoming material
  - Poor design margin to variation
  - Early sensitivity to application of voltage/temperature/current
- Reliability issues (wear-out) drive end of life region
  - Physics of failure related
    - Dielectric breakdown
    - Electromigration
    - Etc..

Reliability of “heritage” satellites > 100kg



- Total sample size = 1584
- >99% operational at time of launch
  - (<1% DOA / Early Fails)
- Continued decreasing reliability as time increases

$$R(t) = e^{-(t/\theta)^{\beta}}$$

$\beta = 0.3875$ $\theta = 8316$ years

Jean-Francois Castet and Joseph H. Saleh. "Satellite Reliability: Statistical Data Analysis and Modeling", Journal of Spacecraft and Rockets, Vol. 46, No. 5 (2009), pp. 1065-1

What about CubeSat reliability…?

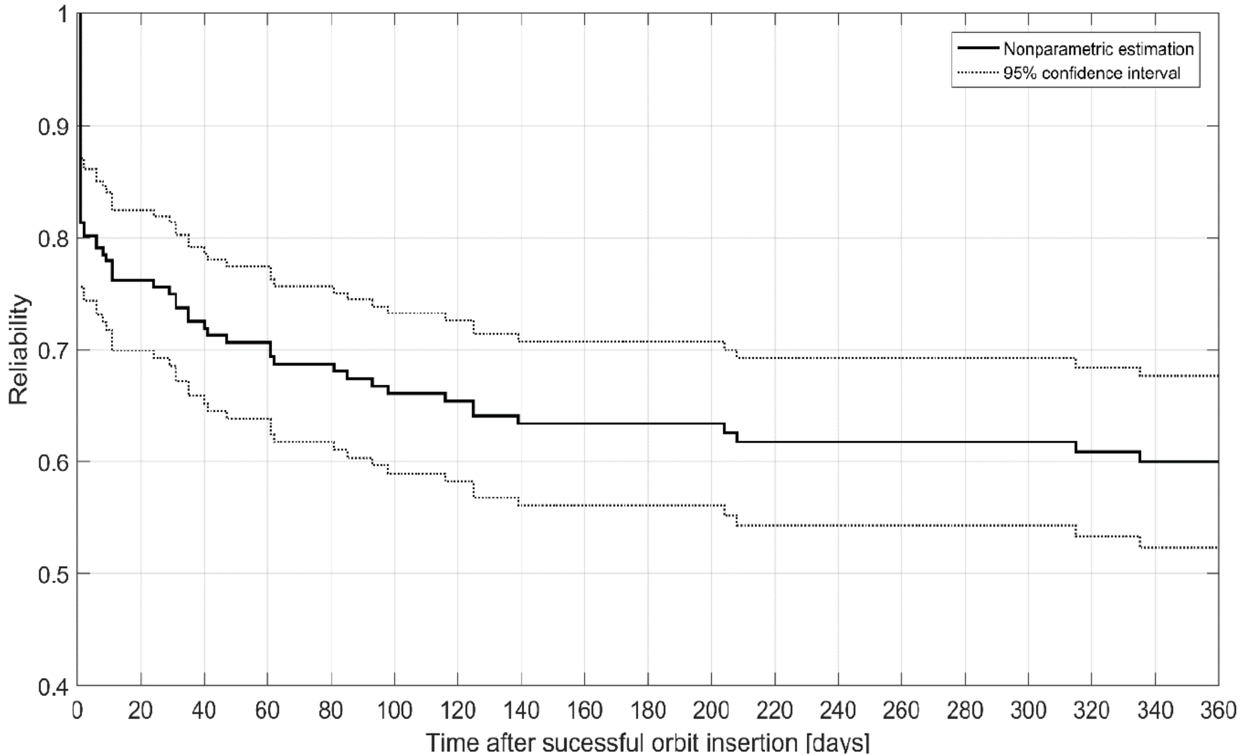


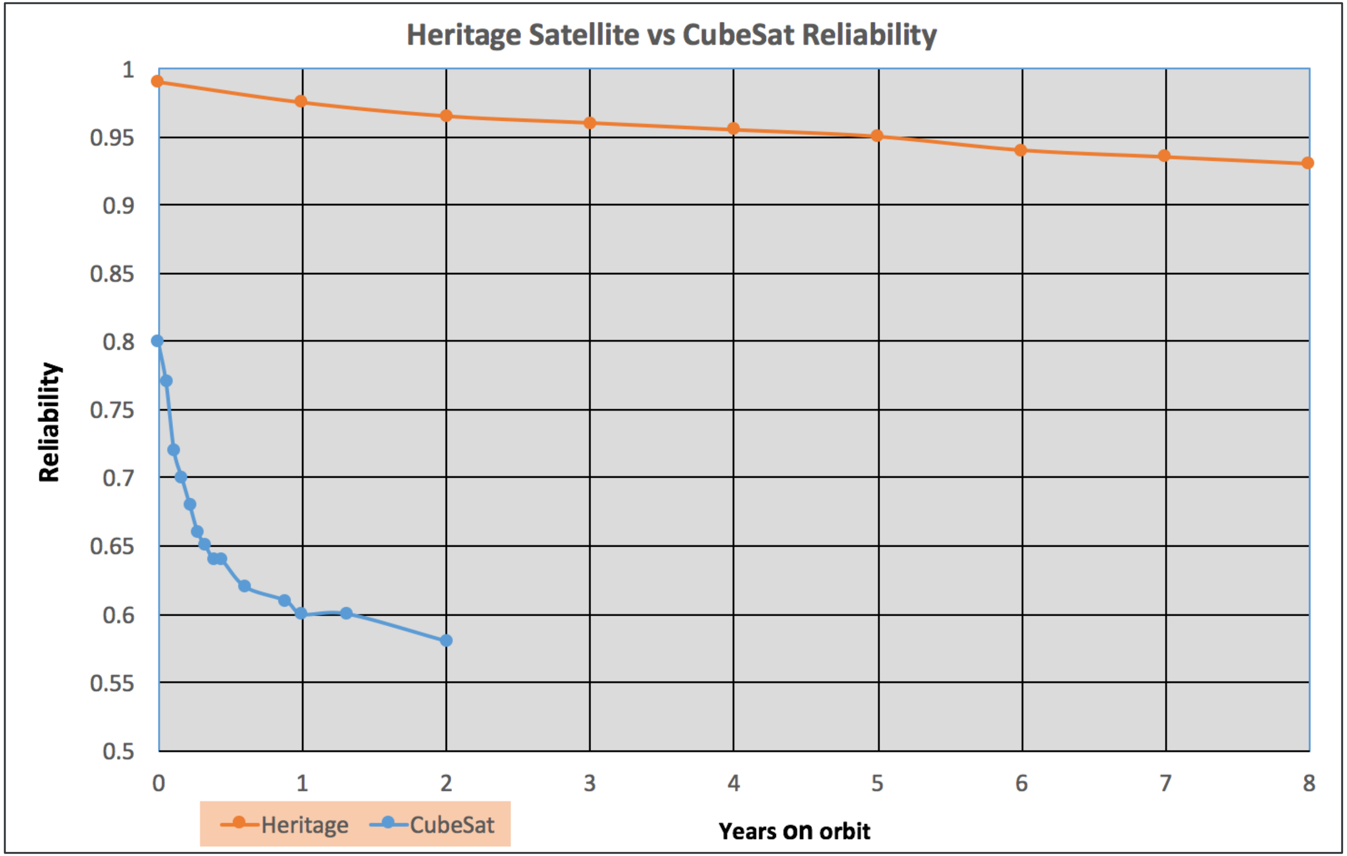
Figure 1: CubeSat reliability with 95% confidence interval – first year in orbit

Reliability of CubeSats – Statistical Data, Developers' Beliefs and the Way Forward, Martin Langer, SSC16-X-2 2016

- 178 CubeSats launched through mid-2014.
- Very steep initial drop in reliability => large number of deployment/DOA failures
- $\boldsymbol{\beta}_1$ = 0.9 (decreasing failure rate)
- $\boldsymbol{\beta}_2$= 1.0 (constant failure rate)

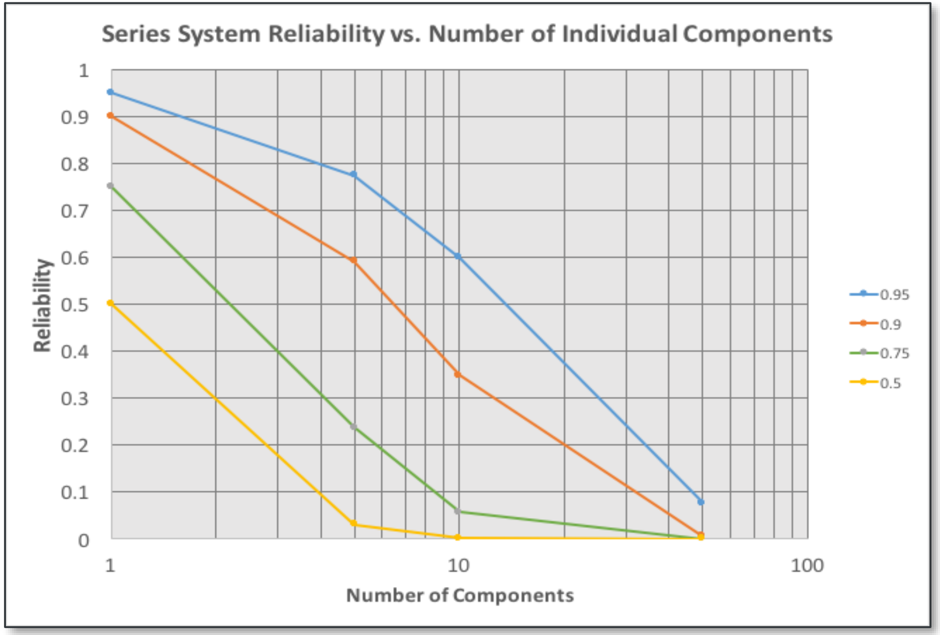
$$R(t) = PNZ\ \alpha_1 \exp\left[-\left(\frac{t}{\theta_1}\right)^{\beta_1}\right] + \alpha_2 \exp\left[-\left(\frac{t}{\theta_2}\right)^{\beta_2}\right]$$

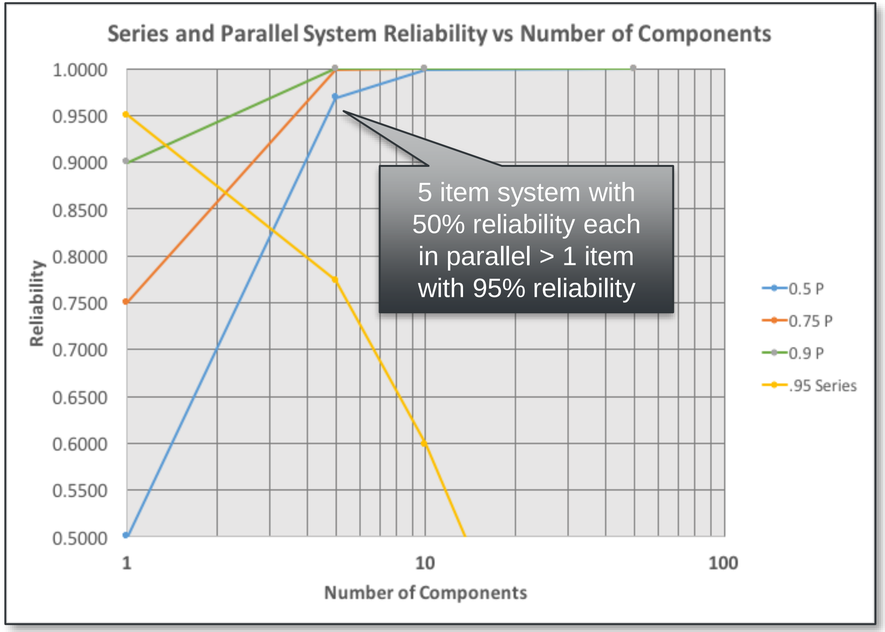
Heritage and CubeSat Reliability Plotted on Same Curve



- Both CubeSat and Heritage show *decreasing* reliability with *increasing* time
- Both CubeSat and Heritage Weibull shape parameter < 1, indicating early failures (“infant mortality”)
- Weibull shape parameter = 1 implies bottom of bathtub/random failure regime
- Implies both types of missions in a failure regime dominated by ***defects*** in design, materials, and variation
- Increasing failure rate with time (ageing/wear out) is not seen
- ***Importance of mission assurance to address defects and quality related issues***

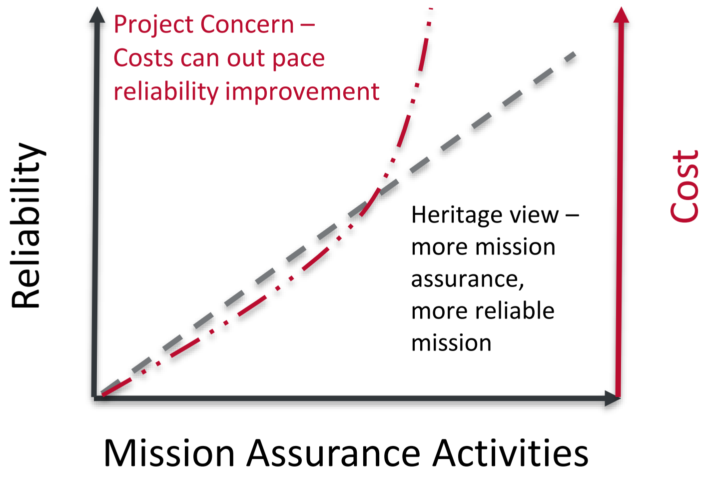
Series and Parallel System Reliability

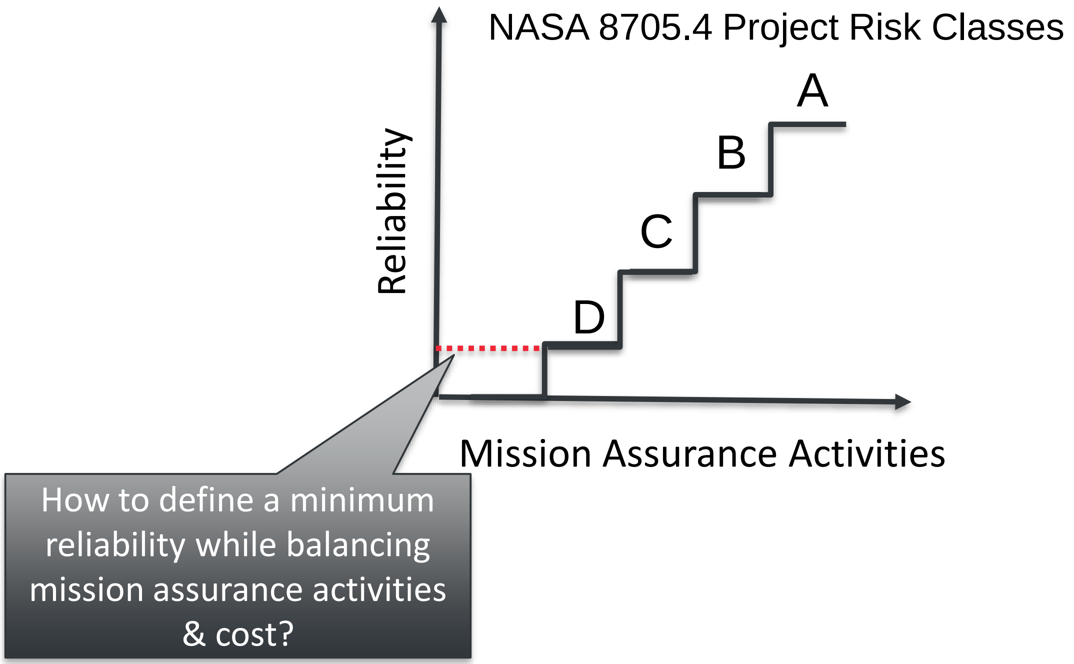




- Series Reliability ($\prod_{i=1}^{n} R_i$) .vs. Parallel Reliability ($1-\prod_{i=1}^{n}[1-R_i]$)
- Parallel system reliability with low reliability items quickly becomes much more reliable than single high reliability item
- All commercial small missions are becoming constellations to take advantage of this concept (along with improvements in performance capabilities).
- Reliability through redundancy and replacement

Relationships of Spacecraft Reliability and Mission Assurance





- JPL developed three project types to address balance between reduced cost and different/increased risk and overall mission reliability

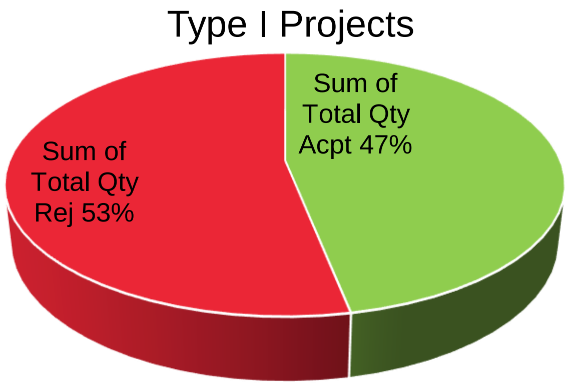
JPL Flight Project Practices and Project Types

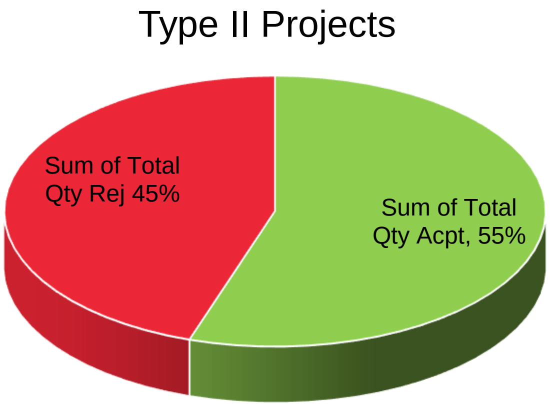
- JPL Flight Project Practices (FPP):
  - Establish standards of uniformity, where standardization is judged to have significant benefit.
  - Capture the approaches and methods important to sponsors.
  - Incorporate lessons learned that were key to past successes, and where deviations created significant problems
  - Identify mandatory practices ("**shalls**") that require management review and approval to waive.
  - Identify guidance ("*shoulds*").
- JPL has defined three types of projects:
  - ***Type I*** primarily contains space flight projects with NPR 8705.4 risk classifications A, B, & C (or equivalent for other sponsors).
  - ***Type II*** primarily contains risk class D space flight projects (or equivalent for other sponsors), or other space flight projects that do not get risk classified (e.g., NPR 7120.8 projects).
  - ***Type III*** primarily contains projects that do not go into space (i.e., sounding rockets, balloons, aircraft payloads, and ground based projects), however, some such projects may still be assigned to Type II.

Tailoring FPP to Type II Missions

- Type II missions are tailored with support of an advisory board
  - Class D / Technology Advisory Board (DTAB)
  - Reduce project cost by changing/reducing scope.
  - Reducing the scope implies different risk posture.
  - Balance reduction in cost from decreasing scope against the change in risk posture.
- Almost all of the Type I FPP (332 total line items) “**shalls**” become “should” for Type II
- Type II “**shalls**” are focused on Quality Assurance
  - Formal plan (QARTA) with customizable choices for given mission risk posture
    - *Receiving/shipping and in-process inspections*
    - *Handling and testing of flight equipment*
    - *Software traceability matrix verification*
    - *“as-tested” and “as-flown” configuration records*
    - *Environmental testing monitoring*
    - *Critical flight movement and facilities inspection/verification*

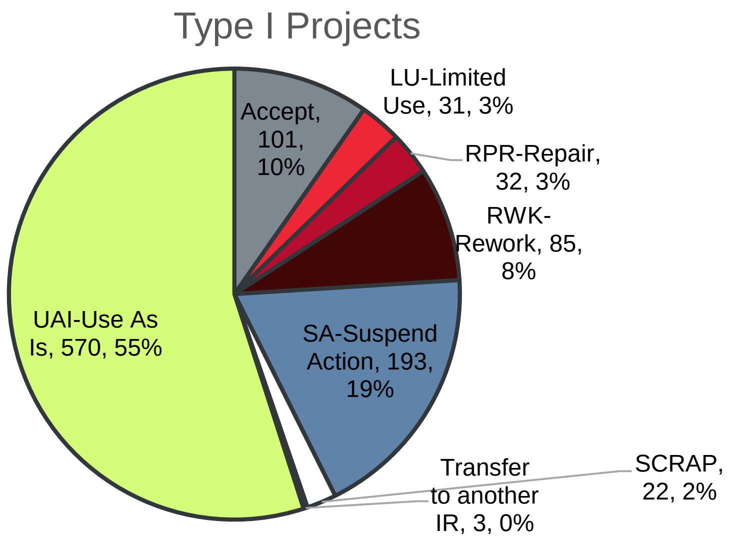
Case Study – Type I vs Type II - HQA In-Process/Testing Inspections
Part Quantity Rejected/Accepted

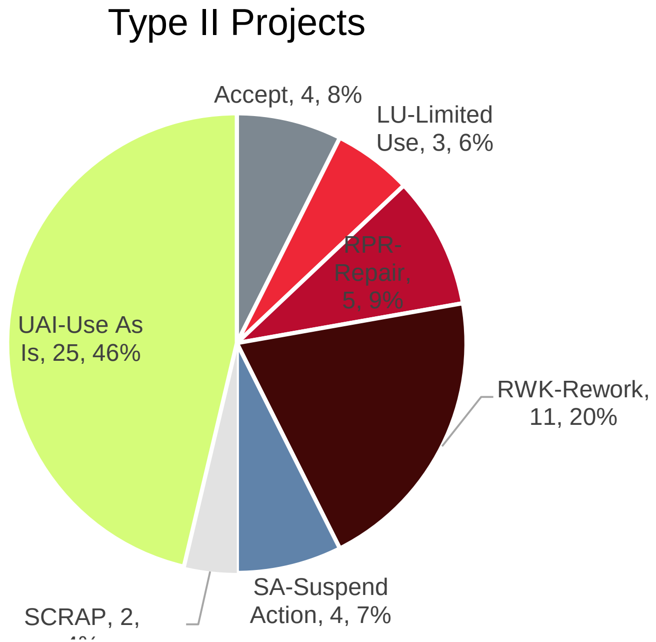




- Percentage rejection rate higher for Type I => additional requirements
- However Type II rejection rate is still significant
- HW used by Type II projects is **not** significantly lower quality (higher defectively)

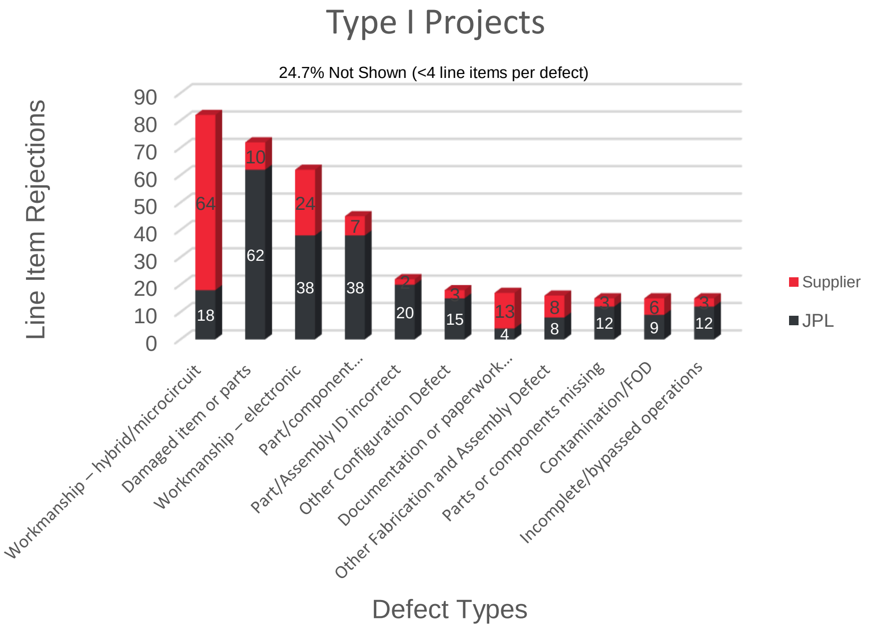
HQA In-Process/Testing Inspections
Dispositions of Rejected Line Items

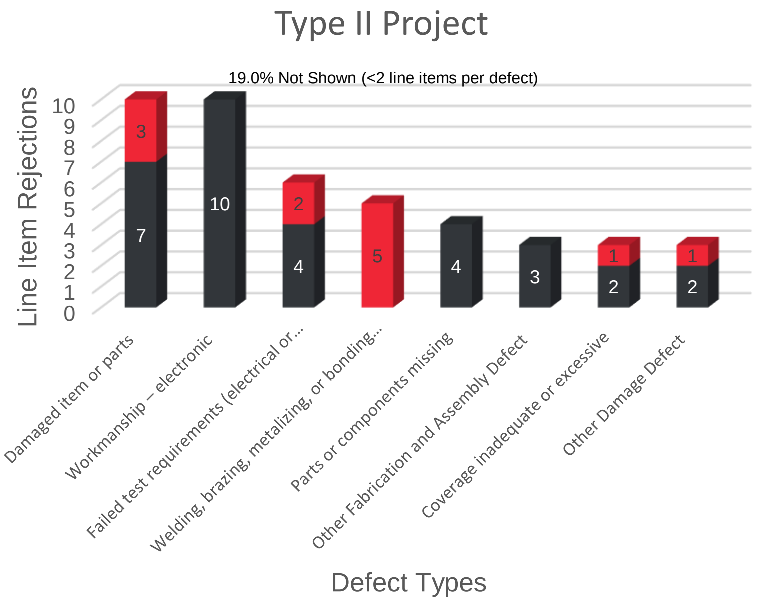




- Type II projects tend to scrap and/or rework more than Type I

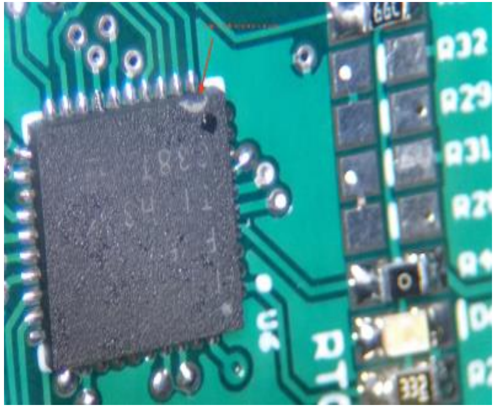
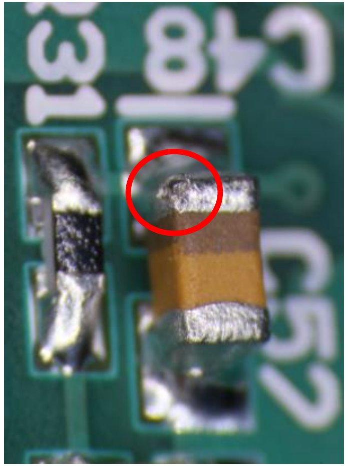
High-Impact HQA In-Process/Testing Defects
with LU/RTV/RPR/RWK/SCRAP Dispositions





- Defects are dominated by workmanship and damage
- Formal defect reduction plans and overall process capability improvement (both internal and external) required

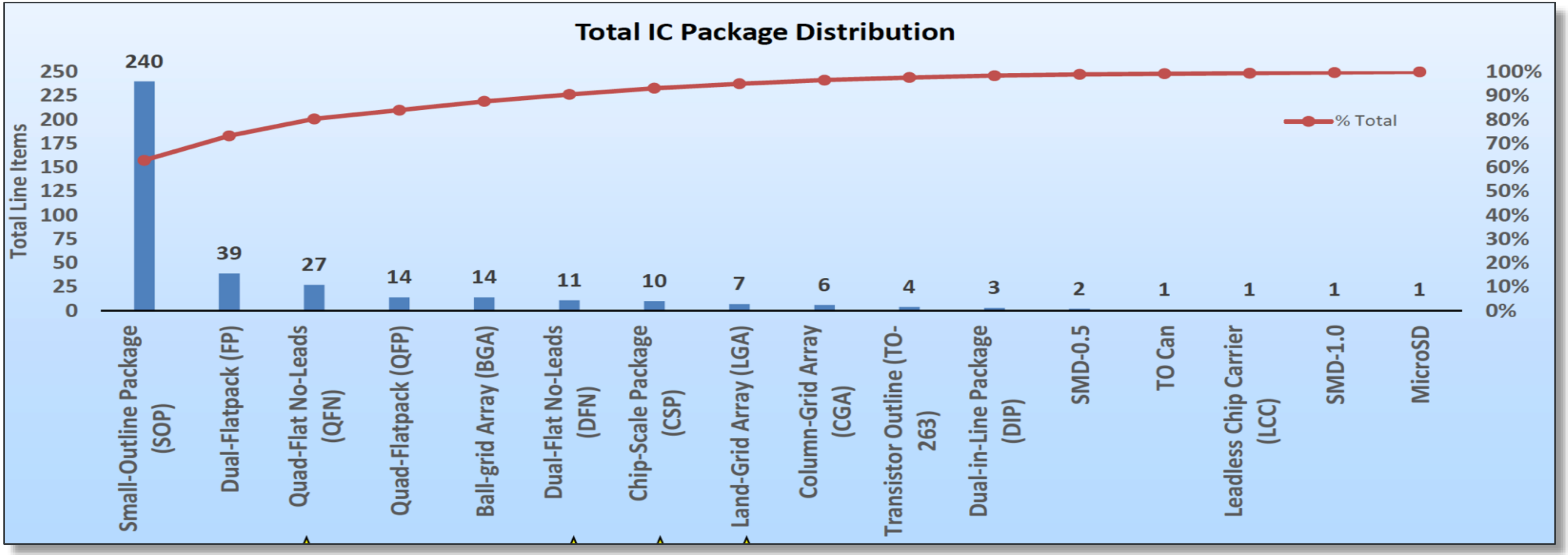
Examples of Type II Defects

Type of Defect	Use-As-Is Disposition Pulled from QARS	Rework Disposition Pulled from QARS
Damage	Damage found on microcircuit. Damage is contained within the package and does not appear to start a crack in the package but more like a chip-out 	C52 has a gouge out of the end cap. Remove and replace C52 with a new part. 

NASA NEPP CubeSat Parts Data Base

- > 2200 individual lines of data
  - Line = Part and corresponding part number
- Consistent trends
  - 33% of total parts are common to at least two or more board designs
  - ~98% of parts are rated for industrial (-40C to 85C) or more temperature
- Almost all passives are SMD 0402 or larger
  - Only 25 parts are listed as SMD 0201, nothing smaller
- Approximately 33% of passives are qualified for automotive use (AEC-Q200)
  - 30% of passives are manufactured by non-QML vendors
  - Polymer tantalum capacitors are 33% of all tantalum capacitors
    - (Special attention required due to moisture sensitivity)

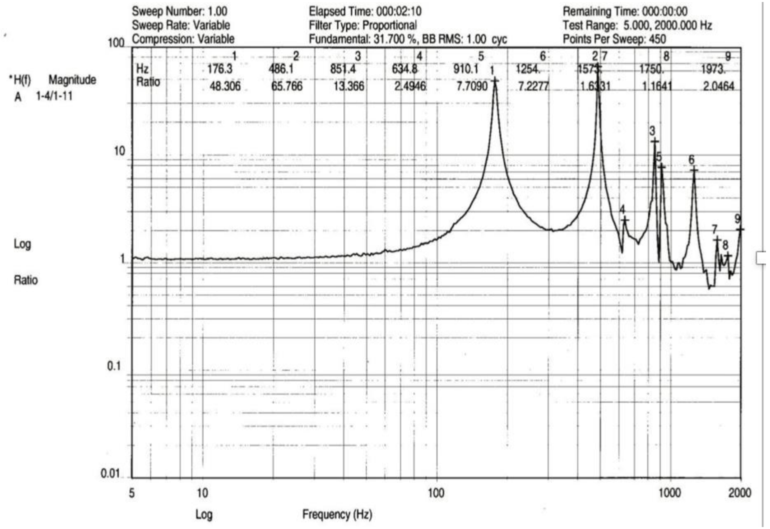
Types of IC Packages used in NASA NEPP CubeSat database

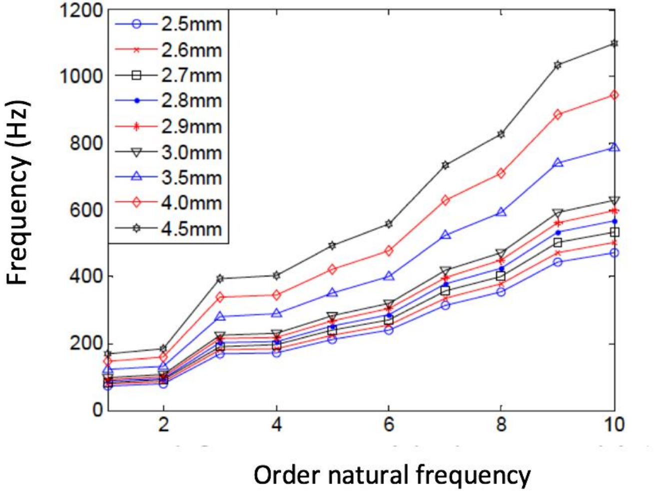


- SOP package types completely dominate
- Being able to handle and process these types of packages will substantially improved quality

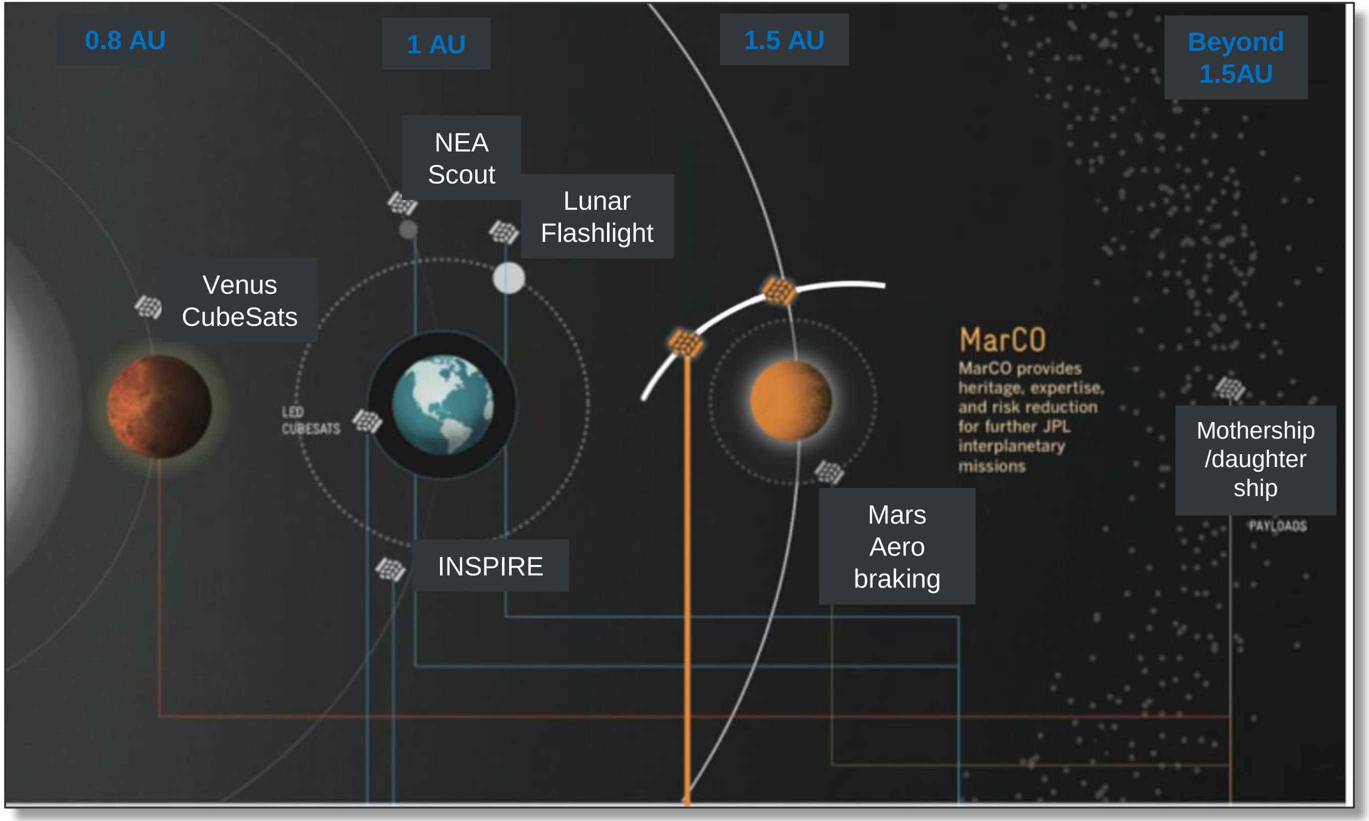
Designing in Quality

- While inspection and verification remain at the heart of identifying and reducing defects, the initial design effort is the key to identifying sensitivity and building in margin to defects
- Mission Assurance evolving to more part of early phase design decisions
  - Example – simulation of PCB mechanical vibration frequency modes
    - Use of thinner/smaller scale COTS can provide significant increase in margin to mechanical vibration





Deep Space CubeSats

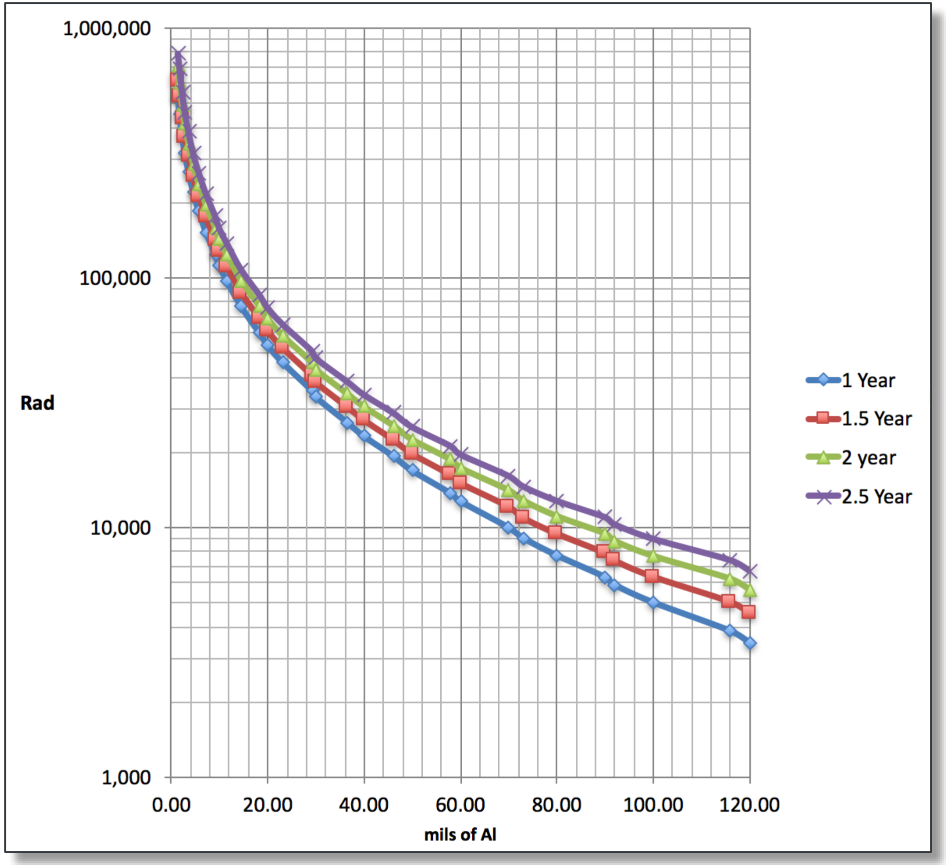


- The first generation of deep space CubeSats is being developed and readied for flight now
- Reliability and Quality issues are being addressed via formal requirements tailoring process based on DTAB method
- Environmental requirements and robust system are critical elements

http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3313&context=smallsat

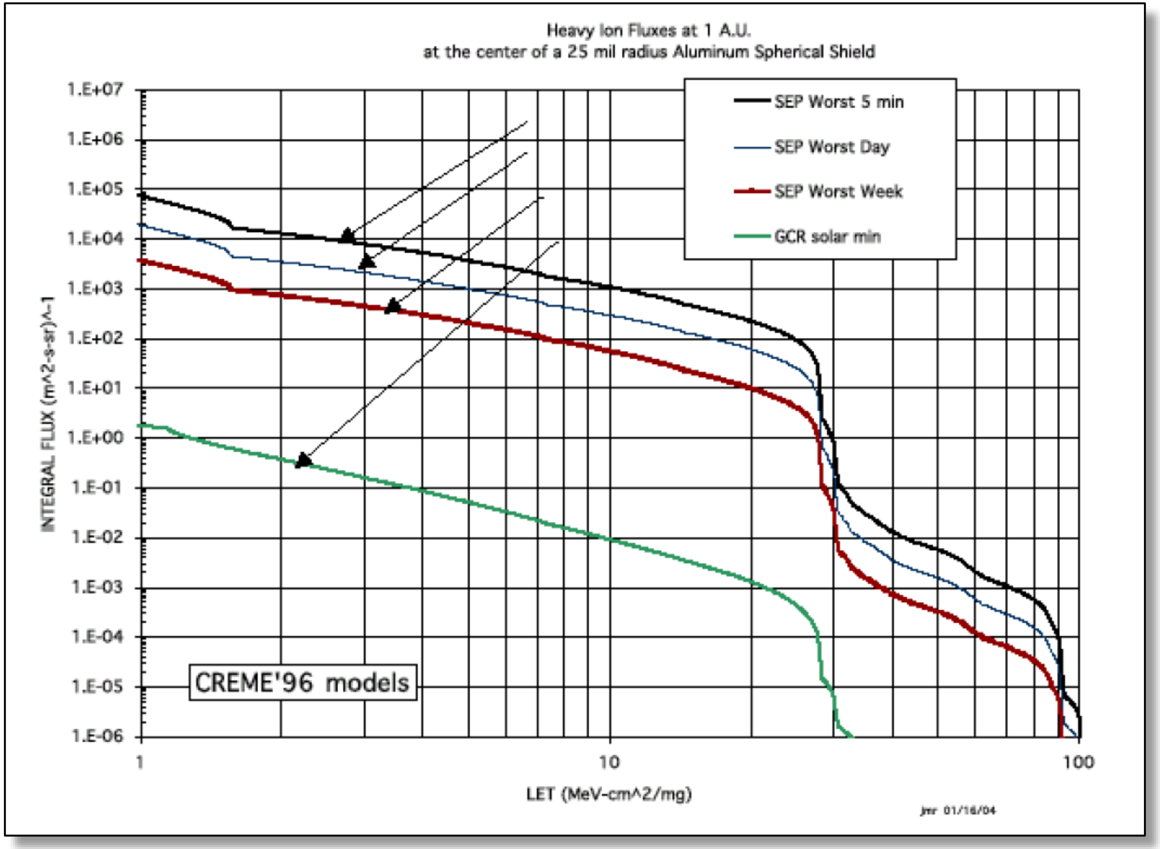
Total Ionizing Dose at 1AU

- Evaluate 1.0 to 2.5 years at 1AU
- Dose as function of Aluminum thickness
- Amount of aluminum shielding will determine EEE parts requirements
- Limited shielding implies use of provide rad-tolerant to rad hard parts, depending on dose level

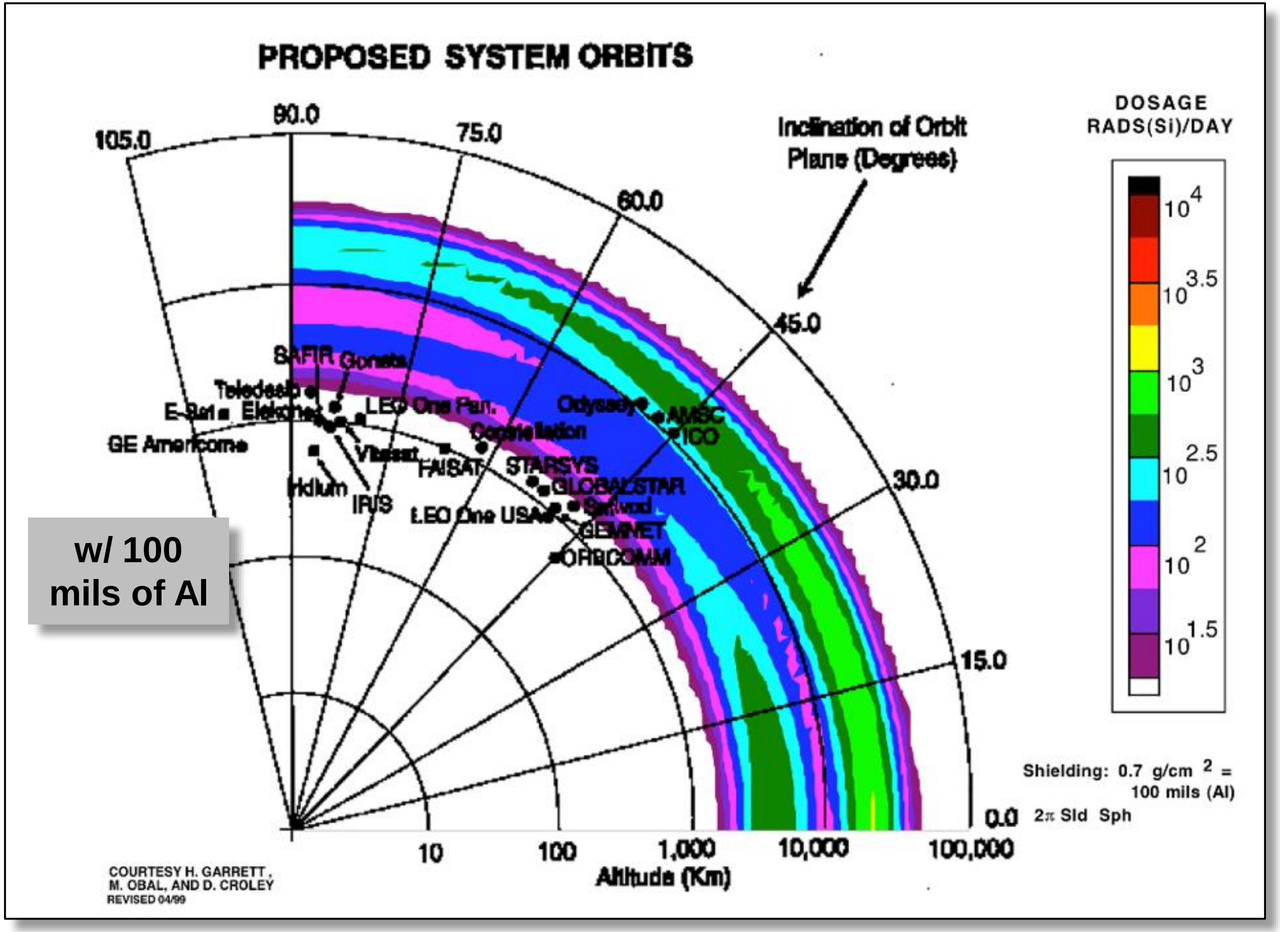


High Energy Solar and Galactic Environment

- Use CREME96 models for Solar Energetic Particle (SEP) Event and GCR Heavy Ion Fluxes. Behind 25 Mils Aluminum Shielding
- Smallsat missions need at least no Single Event Latchup < 37 MeV-cm^2/mg.
- Very difficult/impossible to shield



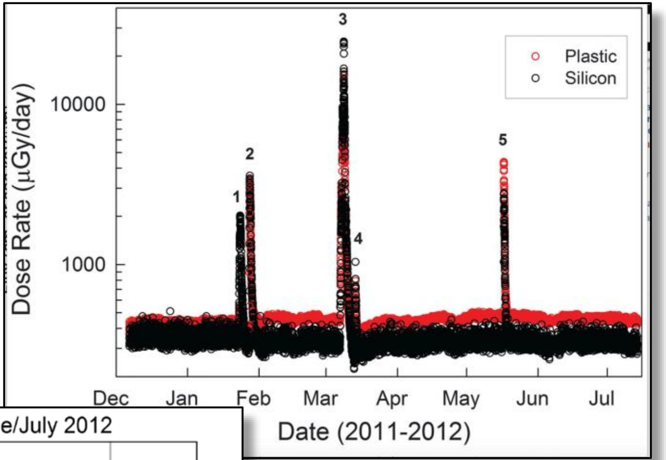
Van Allen Belt Radiation Levels

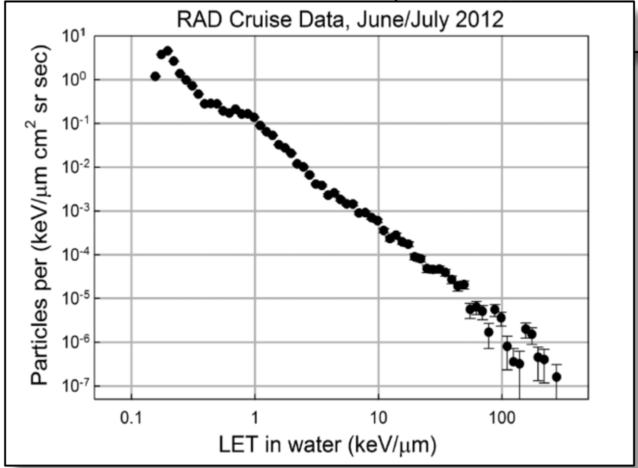


- Transiting Van Allen Belts will also contribute to radiation exposure

Comparison to MSL Martian Transit data measured by RAD instrument

- Averaged 330 µGy/day (0.033 Rad/day) with 5 well defined Solar Energetic Particle (SEP) events occurring during transit
- RAD shielding = most of solid angle shielded at areal density <10 g/cm^2 and the remainder broadly distributed over a range of depths up to 80 g/cm^2
- 253 day (0.7 year) mission = 8.4 rad
- Equivalent dose to human = 0.465 Sievert (46.5 rem)





"*Measurements of Energetic Particle Radiation in Transit to Mars on the Mars Science Laboratory*", C. Zeitlin, et. al. 31 MAY 2013 VOL 340 SCIENCE

Summary

- Small/CubeSats face many of the same defect based quality issues that larger heritage missions face
    - *This results in significant decrease in satellite reliability as mission time increases*
- **Multi-SmallSat constellations are quickly becoming a key mission feature to realize both reliability as well as performance goals**
- Small/CubeSats can still benefit from a formal FPP based design methodology
    - *Tailoring FPP to Small/CubeSat is key contribution/collaboration of S&MA*
- **Emphasis on defect identification and elimination throughout entire assembly and manufacturing processes (internal and external) is where S&MA discipline can be best leveraged to maximize risk mitigation effect for Small/CubeSats**
- Deep Space Small/CubeSats will have to address significant environmental conditions to ensure success

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California Institute of Technology

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